MAGNETIC COUPLED BEAM POSITION MONITOR FOR THE FLASH DUMP LINE

N. Baboi, A. Brenger, D. Lipka[#], J. Lund-Nielsen, K. Wittenburg, DESY, Hamburg, Germany.

Abstract

To measure the beam position at the entrance of the FLASH dump a position monitor has been installed outside of the vacuum in a nitrogen atmosphere. When a charged particle travels through the gas it ionizes the atoms. Therefore the signal from a capacitive button BPM would be contaminated by high backgrounds. To avoid this a magnetic coupled monitor has been designed. The monitor consists of four longitudinal loops symmetrically arranged in the pipe wall. An analytical expression of the signal for this monitor is derived and compared with simulations. Measured data are compared with predictions.

INTRODUCTION

A new diagnostics section before the beam dump has been installed at FLASH [1]. A major component is a new beam position monitor (BPM). The beam exits the vacuum system through a special window before reaching the dump. Its position must be measured here to verify the proper absorption of the beam in the dump. A beam-pipe here connects the exit window to the dump.

The charged particles of the beam ionize the N_2 gas volume between the window and the dump. A 1 GeV electron has an ionization loss of 3 keV/cm in nitrogen. The effective ionization length is the distance between the window and the dump (*l* = 15 cm). The energy loss over this length is 45 keV. According to the production yield [2] this corresponds to about 1300 electron-ion pairs per beam-electron. In the absence of an electric field most of the pairs recombine but some would reach the electrodes of a BPM. In this case the signals of an electric coupled button or stripline BPM would be strongly influenced by the electron-ion pairs [3]. The influence can be drastically reduced by measuring not the electric but the magnetic field of the fast moving charge.

The coupling has been realized with a thin metallic wire forming an electric loop in the pipe. The normal direction of the area of the loop is parallel to the magnetic field of the beam to maximize the signal amplitude. In Figure 1 a sketch of the magnetic coupling is shown. This paper discusses the derivation of analytic expressions for the signal of this BPM and the results are compared with simulations and with measured signals.

[#]dirk.lipka@desy.de

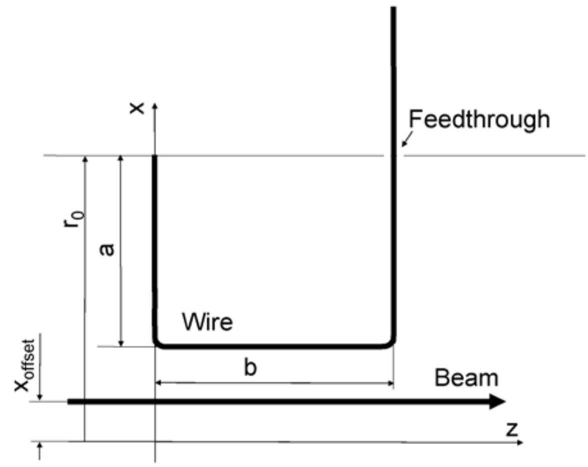


Figure 1: A sketch of one quarter of the detector. A wire forms a loop in the pipe with radius r_0=61.5 mm in the *y* plane and surrounds an area *A* = *a x b*, with *a*=12 mm and *b*=10 mm. The signal is transferred with a feedthrough.

ANALYTICAL SOLUTION

The magnetic field of a beam with current *I(t)* is given by the Biot-Savart rule as

$$\vec{B}(\vec{r},t)=\frac{\mu_0 I(t)}{2\pi\rho}\vec{e}_\phi ,$$

with μ_0 the vacuum permeability and ρ the distance to the *z*-axis in cylindrical coordinates. The beam current can be expressed as

$$I(t)=q_0\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\frac{t^2}{\sigma^2}},$$

with q_0 the beam charge and σ the bunch length in units of time. In Cartesian coordinates the magnetic field is

$$\vec{B}(x',y',t)=\frac{\mu_0 I(t)}{2\pi\left(x'^2+y'^2\right)}\begin{pmatrix}-y'\\ x'\\ 0\end{pmatrix}.$$

The magnetic field with a horizontal offset can be described by a coordinate transformation: $x'=x_{offset}-x$, $y'=y$, $z'=z$, resulting in

$$\vec{B}_1(x_{offset},x,y,t)=\frac{\mu_0 I(t)}{2\pi\left(\left(x_{offset}-x\right)^2+y^2\right)}\begin{pmatrix}-y\\ x_{offset0}-x\\ 0\end{pmatrix}.$$

This field is valid without the beam pipe. To include it a second current is introduced with $I_2(t)$=-*I(t)*. The direction of this current is parallel to the z axis. The distance x_2 to the pipe has to satisfy the following boundary conditions:

- for $x_{offset}=0$: $x_2=\infty$
- for $x_{offset}=r_0$: $x_2=r_0$.

This results in

$$x_2 = \frac{r_0^2}{x_{offset}}.$$

The offset x_2 can be used as a coordinate transformation for a second magnetic field component $\vec{B}_2$:

$$\vec{B}_2(x_{offset}, x, y, t) = \frac{-\mu_0 I(t)}{2\pi\left(\left(\frac{r_0^2}{x_{offset}} - x\right)^2 + y^2\right)} \begin{pmatrix} -y \\ \frac{r_0^2}{x_{offset}} - x \\ 0 \end{pmatrix}.$$

The resulting magnetic field is

$$\vec{B}(x_{offset}, x, y, t) = \vec{B}_1(x_{offset}, x, y, t) + \vec{B}_2(x_{offset}, x, y, t)$$

for the range $x_{offset} \in \{-r_0 + a, r_0 - a\}$ and $y=0$. For an offset in the vertical plane one can exchange x and y accordingly.

The magnetic flux is given by

$$\Phi(x_{offset}, t) = \int \vec{B}(x_{offset}, x, y, t) \cdot d\vec{A},$$

with the area $d\vec{A} = dxdz\vec{e}_y$, see Figure 1. Here only the vertical component of the magnetic field contributes to the flux which results in

$$\Phi(x_{offset}, t) = \frac{\mu_0 I(t)}{2\pi} \int_{x=r_0-a}^{r_0} \int_{z=0}^{b} \left(\frac{1}{x_{offset} - x} - \frac{1}{\frac{r_0^2}{x_{offset}} - x} \right) dxdz$$

$$= \frac{\mu_0 I(t) b}{2\pi} \left[E(x_{offset}) - F(x_{offset}) \right]$$

with $E(x_{offset}) = \ln\left(\frac{x_{offset} - r_0 + a}{x_{offset} - r_0} \right)$

and $F(x_{offset}) = \ln\left(\frac{r_0^2 - r_0 x_{offset} + a x_{offset}}{r_0^2 - r_0 x_{offset}} \right)$.

Here the beam offset has been removed from the numerator so that the equation can also be used for $x_{offset}=0$. The induced voltage is

$$U(x_{offset}, t) = -\frac{d\Phi}{dt}$$

$$= -\frac{\mu_0 b}{2\pi} \left[E(x_{offset}) - F(x_{offset}) \right] \frac{dI(t)}{dt}$$

with

$$\frac{dI(t)}{dt} = -q_0 \frac{1}{\sigma^3 \sqrt{2\pi}} t e^{-\frac{1}{2}\frac{t^2}{\sigma^2}}.$$

One can see that the voltage strongly depends on the bunch length. The amplitude is located at the bunch length $t = \pm\sigma$ and depends linearly on the area A.

To measure the position in a plane, introduce two opposite wires and calculate the individual amplitudes

$$U_1 = U(x_{offset}, \sigma) = D \frac{q_0}{\sigma^2} \left[E(x_{offset}) - F(x_{offset}) \right],$$

with $D = \mu_0 b e^{-1/2} / \left(2\pi\sqrt{2\pi}\right)$ and

$$U_2 = U(-x_{offset}, \sigma) = D \frac{q_0}{\sigma^2} \left[E(-x_{offset}) - F(-x_{offset}) \right].$$

When the offset tends to be zero the second term (F) also approaches zero. Using the difference-over-sum-method one gets:

$$Q = \frac{\Delta}{\Sigma} = \frac{U_1 - U_2}{U_1 + U_2}.$$

Here the dependencies of the bunch length and charge are eliminated. Applying this method one can measure the beam offset. The sensitivity S depends only on the radius r_0:

$$S = \left. \frac{dQ(x_{offset})}{dx_{offset}} \right|_{x_{offset}=0}$$

Note that the above equations for the voltage are only applicable for an offset in one plane.

SIMULATIONS

The cross section of the beam-pipe in front of the beam dump is an octagon, as shown in Figure 2. The distance between two opposite planes is 123 mm. Each wire forms a loop with an area of A=120 mm^2. The wire has a diameter of 1 mm. The design has been transferred to the simulation tool CST [4]. The beam is simulated longitudinally as a Gaussian distribution, a total charge of 2.5 nC and a bunch length of 660 ps; these parameters are chosen to compare with the measurement. Figure 3 shows the shape of the voltage of two opposite sensors from the calculation and the simulation with an offset of 10 mm. The analytical expressions clearly agree very well with the results of the simulations.

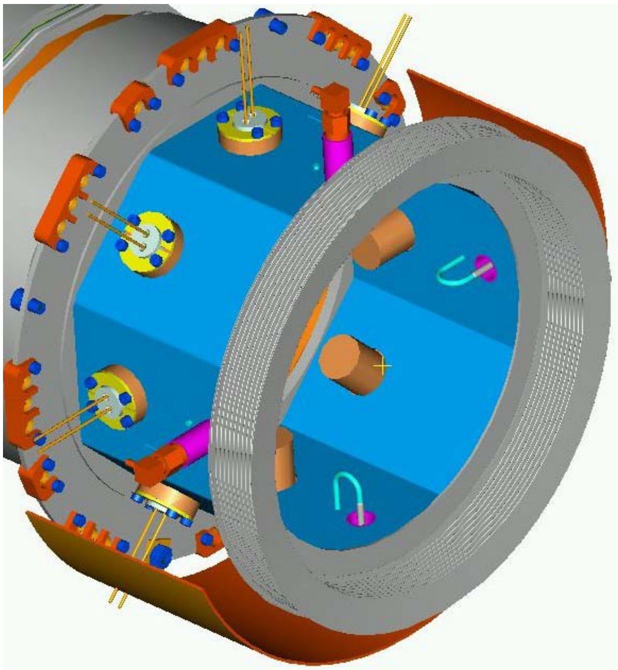


Figure 2: Construction view of the end of the beam-pipe in front of the dump. Two wire-loops are visible.

In addition the difference-over-sum-method has been calculated analytically and simulated and the results are shown in Figure 4. They are in very good agreement; the calculation describes even the non-linearity at large offsets. The slope at x_{offset}=0 gives the sensitivity to be S=0.032/mm. This is comparable to a button BPM with the same pipe diameter and a button diameter of 20 mm, (which results in S_{button}=0.022/mm [5]).

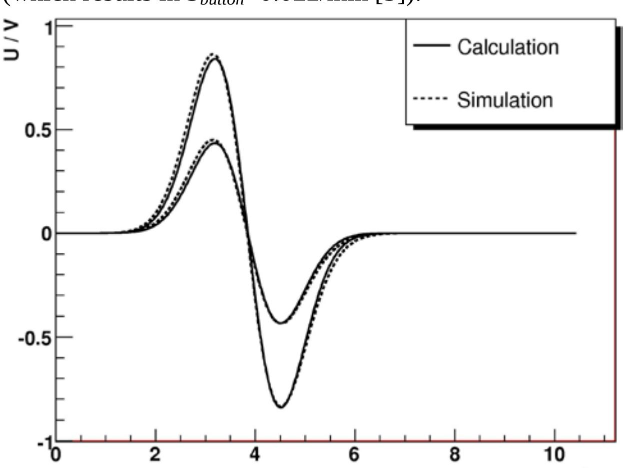


Figure 3: The time response from the analytic calculations and from the simulations for the magnetic coupled BPM for a charge of 2.5 nC, bunch length of σ_z=660 ps and an offset of 10 mm for two opposing sensors.

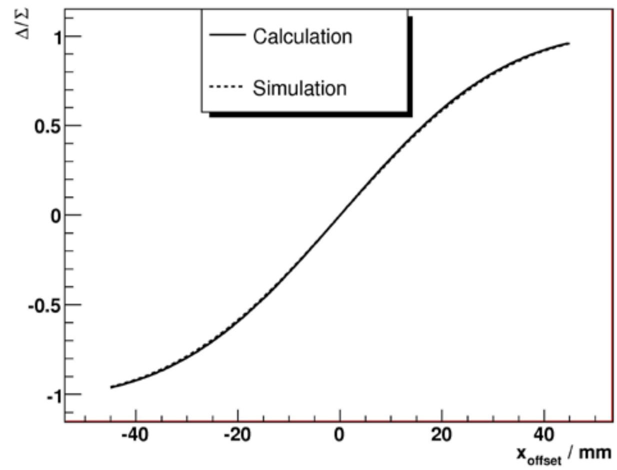


Figure 4: The difference-over-sum as a function of beam offset for the analytic and simulation methods. The results are in very good agreement; so much so that it is difficult to distinguish the lines. The slope at x_{offset}=0 corresponds to the sensitivity.

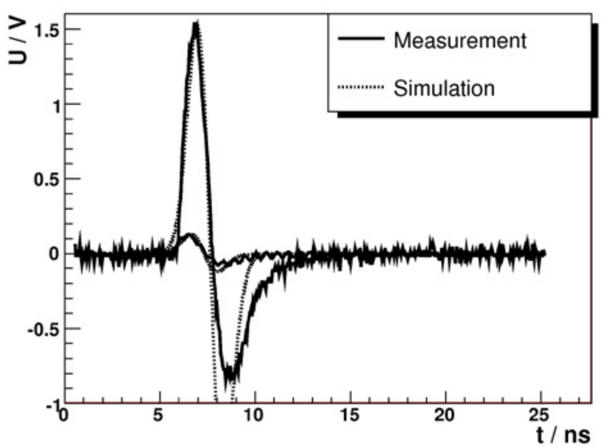
MEASUREMENTS

The new diagnostics section in front of the dump was built and installed at FLASH before the start of a 9 mA study-run in Sept. 2009. In Figure 5 the beam-pipe with the BPM is shown.

Figure 5: The end of the diagnostics beam line with the wire-loops. The 8 cylinders upstream of the wire loops contain beam halo monitors [1].

The beam measurements were done during the 9 mA study-run. During this time the bunch-charge was not the typical value of 1 nC, but 2 to 3 nC; for this measurement it was 2.5 nC. The actual bunch length is much shorter than 660 ps, which was taken for the calculations and simulations. But the cable between the BPM and the rack room acts as a low-pass filter such that higher frequency components are attenuated. In addition a low-pass filter with 200 MHz threshold (with 3 dB attenuation) was used to filter the first TEM mode of the beam-pipe, which is approximately 1.71 GHz. (This is lower than the corresponding frequency for a round tube of 1.75 GHz due to the octagonal shape). The longer bunch length assumed in the calculations and simulations corresponds to the signal after the cable and low-pass filter.

The measurements of the signals from all four wires of the BPM are compared with the simulation in Figure 6 (the analytical solution is not shown because the beam has large offsets in both planes). The measurements were taken with a Tektronix TDS 6604 oscilloscope. The attenuation of the cables and the low-pass filter has been corrected in the measurement. Therefore one can see the low-pass filtered amplitude of the beam at the exit of the BPM. The measurement corresponds to a horizontal beam offset of 39 mm and a vertical offset of 16 mm. In the positive branch of the amplitudes there is good agreement between measurement and simulation. The negative amplitudes of the measurement are smeared out due to the cables and low-pass filter. Nevertheless, the simulation results predict well the voltage distribution for all beam positions. The good agreement also indicates a negligible influence of the ionization products on the BPM readings.



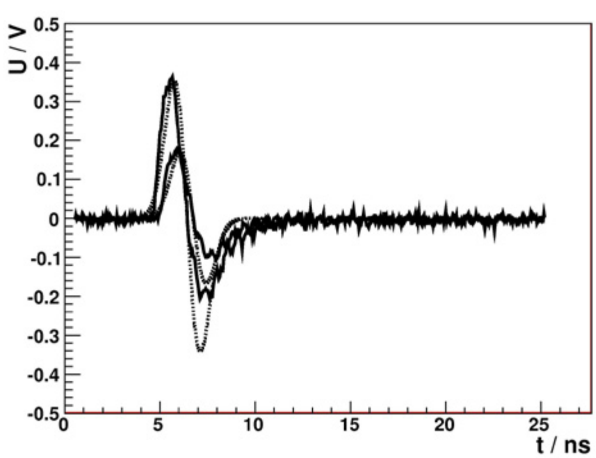


Figure 6: The signal voltage as a function of time from all wires of the BPM. The upper diagram shows the two opposing wire for the horizontal plane, the lower diagram shows the corresponding wires for the vertical plane The amplitudes are corrected for the attenuation of the cables and low-pass filter. The results of the simulations are included with a bunch length of σ_z=660 ps and a bunch charge of 2.5 nC.

SUMMARY

A BPM is introduced directly in front of the FLASH beam dump. The BPM is positioned outside of the vacuum system in a nitrogen atmosphere. A magnetic coupled BPM has been chosen to avoid the distortion of the signals from the ionized electron-ion pairs. The derivation of analytic expressions of the voltage as a function of time from a magnetic coupled BPM is presented and the results compared with simulations. Both are in good agreement. The sensitivity is comparable to that of a button BPM. The device has been manufactured at DESY and installed in the dump line. The first measurements show good agreement with the simulations. No influence of the ionization products on the signals could be detected.

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